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Approaches to ecological sustainability in sub-Saharan Africa: Evaluating the role of globalization, renewable energy, economic growth, and population density

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ABSTRACT

Addressing the intertwined challenges of economic growth and environmental sustainability is essential to mitigate the worsening impacts of climate change in sub-Saharan Africa (SSA). Promoting clean energy adoption and understanding the role of globalization have been identified as critical strategies to enhance environmental quality while fostering sustainable economic progress. However, empirical focus on the SSA context remains limited, particularly regarding ecological footprints as a measure of environmental sustainability. This study investigates the effects of globalization, renewable energy consumption, economic growth, trade openness, and population density on SSA nations' ecological footprint and CO_2 emissions from 1994 to 2021. To ensure robust and reliable findings, advanced econometric techniques—namely Panel-Corrected Standard Errors (PCSE), Feasible Generalized Least Squares (FGLS), and Driscoll-Kraay estimators—are employed to address heterogeneity and cross-sectional dependence issues prevalent in panel data. The results identify three key findings: firstly, globalization has a double-edged effect on environmental outcomes in SSA, increasing the ecological footprint significantly but reducing CO_2 emissions; secondly, renewable energy consumption is a critical determinant for environmental improvement, significantly reducing both ecological footprints and CO_2 emissions; and finally, economic growth degrades the environment, resulting in a significant increase in both ecological footprints and CO_2 emissions. Additionally, the Dumitrescu-Hurlin panel causality test further uncovers bidirectional relationships between most explanatory variables and environmental indicators. Based on these findings, the study recommends that SSA countries prioritize investments in renewable energy infrastructure, adopt stricter environmental regulations, embrace green technologies to promote sustainable economic growth and leverage urbanization and infrastructure development.

1. Introduction

The role of globalization and renewable energy consumption in shaping environmental sustainability has become increasingly critical in today's interconnected world. While globalization has spurred economic growth and development, it has also significantly contributed to environmental degradation through heightened resource extraction and pollution (Asongu & Odhiambo, 2019). Key drivers exacerbating this degradation include rapid population growth, accelerated urbanization, burgeoning industrialization, and the intensification of globalization, all of which lead to increased consumption and production (Terzi & Pata, 2020; Warsame et al., 2023). According to the Intergovernmental Panel on Climate Change [IPCC] (2023), global temperatures have risen by approximately 1.1 °C since the pre-industrial era, with projections indicating a potential rise of 3.2 °C by 2100 if current climate policies persist. This warming trend has already resulted in severe impacts, including more frequent and intense weather extremes, adversely affecting sectors such as agriculture, tourism, fisheries, energy, and forestry on a global scale (Abdi et al., 2023). Amidst these challenges, renewable energy presents a promising pathway to reducing ecological footprints by decreasing dependence on fossil fuels and lowering greenhouse gas (GHG) emissions (Zoundi, 2017). However, the non-

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alignment of climate and energy policies in developing countries poses significant challenges to achieving sustainable development (Salari et al., 2021). Researchers are actively seeking to develop impactful strategies that forge efficient connections between energy consumption and resource utilization. Such strategies promote sustainable, cost-effective growth while addressing environmental issues (Langnel & Amegavi, 2020). Aligning energy policies with climate goals is essential for advancing sustainability and mitigating the adverse environmental impacts of globalization.

Globalization, which involves the interconnections and interdependencies of economies, has transformed the world through the exchange of products, culture, and ideas (Sahoo & Sethi, 2021; Abdi & Hashi, 2024). While offering numerous advantages, globalization has also severely impacted the environment, leading to resource depletion, increased pollution, waste generation, and loss of biodiversity (Kassouri & Alola, 2022). The acceleration of industrial activities due to globalization results in higher energy consumption and carbon emissions, exacerbating climate change (Asongu & Odhiambo, 2019). Rapid urbanization and infrastructure development associated with globalization contribute to habitat destruction and increased ecological footprints (Okelele et al., 2022). Moreover, the global demand for raw materials often leads to the overexploitation of natural resources, which results in unsustainable extraction practices (Nathaniel et al., 2020). Besides, energy consumption significantly contributes to countries' economic growth globally, but its environmental impact varies depending on the nature of the energy resources consumed (Guo et al., 2023). However, renewable energy resources produce significantly fewer pollution emissions than non-renewable resources like fossil fuels. The adoption of renewable energy helps decrease air and water pollution, thereby improving public health and reducing environmental damage (Jacobson & Delucchi, 2011). Additionally, integrating renewable energy into globalized economies supports sustainable economic growth by providing reliable energy sources and creating green jobs (REN21, 2021). In densely populated areas, renewable energy can alleviate the environmental pressures associated with high energy demand and urbanization (Sahoo & Sethi, 2021).

In the context of sub-Saharan Africa (SSA), significant challenges related to energy deprivation and environmental sustainability persist. The implementation of renewable energy offers substantial promise for addressing these issues (Wang et al., 2022). The region is endowed with abundant natural resources, such as sunlight, water, and wind, which can be harnessed to meet energy needs without compromising environmental integrity (Abdi, 2023). Currently, many countries in SSA rely on natural biomass fuels for routine cooking and heating, which leads to indoor air pollution and various health issues (Abdi & Hashi, 2024; Dingru et al., 2023). In 2017, approximately 57 % of the population in SSA, or about 600 million people, lacked access to electricity (Ojong, 2022). In the early 1990 s, many African countries experienced demographic shifts that led to urban population distribution challenges, resulting in numerous environmental and socio-economic issues, such as food and water scarcity and ecological and land depletion (Baye et al., 2021). Additionally, water supply schemes in the SSA region have increasingly shifted from groundwater to surface water sources like rivers. This shift, combined with rapid urbanization and limited water resources, has significantly reduced per capita water availability (Kassouri & Alola, 2022). According to the Global Footprint Network (2022), Western and Southern Africa have experienced a notable increase in their ecological footprint, surpassing biocapacity and leading to an ecological deficit. Eastern Africa displays a similar pattern, with its ecological footprint exceeding biocapacity since 2005. In contrast, Middle Africa has maintained an ecological surplus, with biocapacity meeting or exceeding the ecological footprint.

However, despite the potential of renewable energy in SSA, numerous obstacles persist, including infrastructure deficits, financial limitations, policy inconsistencies, technology gaps, and challenges with community acceptance (Abdi, 2023). To achieve a sustainable equilibrium, there is an urgent need to transition to renewable energy sources like solar, wind, and hydropower, which have minimal environmental impact and can alleviate energy poverty (Salahuddin et al., 2020). Renewable energy projects not only reduce dependence on fossil fuels but also provide environmentally friendly solutions for preserving ecosystems and biodiversity (Adekoya et al., 2022). Reducing the ecological footprint in SSA necessitates that renewable energy initiatives align with regional environmental concerns. For example, decentralized solar energy systems can be installed in rural areas without the need for large, rigid infrastructure (Ibrahiem & Hanafy, 2020). The rate of resource degradation in SSA often outpaces conservation efforts, suggesting the urgency of investigating the role of globalization and renewable energy in mitigating ecological footprints. The transition from non-renewable to renewable energy consumption is aligned with several United Nations Sustainable Development Goals [SDGs], such as SDG 3 [good health and well-being], SDG 7 [affordable and clean energy], SDG 11 [sustainable cities and communities], and SDG 13 [climate action] (Eryiğit, 2021). Integrating renewable energy resources into national policies can significantly mitigate environmental impacts and provide more sustainable solutions for the region (Abdi & Hashi, 2024; Saint Akadiri et al., 2019).

The measurement of ecological assets required by the current population to produce natural resources for consumption is termed human demand. Numerous efforts have been made to quantify the human energy necessary to sustain the existing development configuration (Guo et al., 2023). As the global population continues to grow, waste generation and resource demand also escalate, which necessitates a shift in current energy consumption patterns to reduce the ecological footprint (Nathaniel et al., 2020). Bio-capacity, on the other hand, measures the Earth's ability to produce these natural resources (Okelele et al., 2022; Onifade, 2023). Over the decades, increasing human demands have consistently exerted pressure on the ecology, affecting land use, resource depletion, and extraction. Globalization has exacerbated these pressures by accelerating industrial activities and expanding consumption patterns (Asongu & Odhiambo, 2019). This highlights the effects of globalization on the ecological footprint (Okelele et al., 2022). The ecological footprint measures the consumption of natural resources and environmental impacts, such as land degradation, climate changes, pollution, and biodiversity loss (Guo et al., 2023). Consequently, the global ecological footprint has been rising, leading to unsustainable levels of resource use and environmental degradation (Wackernagel & Beyers, 2019). Previous studies have frequently used CO_2 emissions as a primary indicator of environmental impact. The ecological footprint is a more comprehensive measure than CO_2 emissions, encompassing resource consumption, waste, and biodiversity loss, allowing for a holistic assessment of human impact on ecosystems (Wackernagel & Beyers, 2019).

Given this background, this study aims to investigate the effects of globalization, renewable energy utilization, economic growth, trade liberalization, and urbanization on the ecological footprint and carbon emissions in 34 selected African countries using panel data from 1994 to 2021. This research addresses critical gaps in the existing literature and introduces insightful policy perspectives. Firstly, while previous studies have primarily focused on CO_2 emissions, we expand the scope to include ecological footprints, which provides a more comprehensive measure of environmental impact. This is particularly relevant for SSA, a region grappling with resource depletion and rapid urbanization. Secondly, unlike prior research that often examines isolated factors or specific regions, this study integrates these variables into a single model, offering a holistic view of their combined effects. By focusing on SSA, the analysis identifies region-specific trends and policy implications, thus extending the geographical scope beyond previous studies. Thirdly, the study employs advanced econometric techniques such as Panel-Corrected Standard Errors (PCSE), Feasible Generalized Least Squares (FGLS), and Driscoll-Kraay estimators, which effectively address cross-sectional dependence and heterogeneity, thereby enhancing the robustness of our findings. Given the economic and trade spillovers among SSA countries, these methodologies ensure that our policy instruments demonstrate cross-regional dependence and account for structural differences. Finally, the study provides policy recommendations based on the results, which emphasize the promotion of renewable energy adoption to mitigate ecological footprints, the design of trade policies that enhance environmental sustainability, and the implementation of urban planning strategies that account for the environmental impacts of increased urbanization and economic growth.

The remainder of the paper is organized as follows: Section 2 provides a comprehensive review and synthesis of recent empirical literature on the topic. Section 3 details the sampling, variables, and empirical strategy. Section 4 presents the results along with an in-depth discussion. Finally, Section 5 concludes with policy insights based on the findings.

2. Literature review

Recent scholarly investigations have extensively investigated the effects of globalization, renewable energy utilization, economic growth, trade liberalization, and urbanization on the ecological footprint and carbon emissions across different regions. With the urgent global mandate to combat climate change, this association has become a focal point in contemporary academic discourse. The empirical studies in this realm have yielded diverse outcomes, largely due to variations in methodologies, selected variables, and the developmental stages of the nations involved. By synthesizing insights from a broad spectrum of academic sources, this review critically examines the effects of trade openness, renewable energy consumption, economic growth, and globalization on environmental sustainability.

Globalization has been found to significantly increase carbon emissions and ecological footprints across different regions and periods. Sultana et al. (2023) studied the Next-11 countries from 1990 to 2019, using heterogeneous panel cointegration tests and the method of moments quantile regression. Their findings indicate that globalization significantly increases CO_2 emissions, with a greater impact observed at higher quantiles. Similarly, Sabir and Gorus (2019) analyzed South Asian countries from 1975 to 2017 using the panel autoregressive distributional lag (ARDL) model. They concluded that economic globalization significantly increased the ecological footprint, while technological changes had an insignificant impact. Rudolph and Figge (2017) extended this analysis to 146 countries from 1981 to 2009. Their outcomes highlighted that economic globalization increased ecological footprints in consumption, production, imports, and exports. Moreover, Mahmood et al. (2024) revealed that sustainable supply chain practices, such as green logistics and resource-efficient operations, significantly enhance environmental sustainability. This indicates a broad and pervasive influence of globalization on environmental outcomes. On the other hand, localized studies provide additional insights into the specific impacts of globalization on different regions. Usman et al. (2020) examined the impact of globalization on the ecological footprint in the USA from 1985 to 2021 using the ARDL approach. They found that globalization positively affects the ecological footprint in both the short- and long-term. In Malaysia, Ahmed et al. (2019) found that while globalization is not a significant determinant of the ecological footprint, it increases the carbon footprint. Their analysis, utilizing Bayer-Hanck and ARDL tests, showed that energy consumption and economic growth are primary drivers of ecological footprints, while population density reduces them.

As evidenced by several studies, renewable energy consumption plays a crucial role in mitigating ecological footprints and promoting environmental sustainability. Tariq et al. (2024) demonstrated that in G7 nations, green energy finance, governance, and hydropower consumption significantly reduce ecological footprints. Similarly, Ansari et al. (2021) found that in leading renewable energy-consuming countries from 1991 to 2016, renewable energy significantly reduced ecological footprints, which implies its potential to alleviate environmental pressures. In Somalia, Abdi et al. (2024) used the ARDL model and dynamic OLS to show that renewable energy reduces both ecological footprints and CO_2 emissions in the short- and long-term. Similarly, Caglar et al. (2021) demonstrated that in countries with severe environmental degradation, renewable energy consumption mitigates environmental harm, which reinforces its environmental benefits. Additionally, Abdi (2023) investigated 41 SSA countries between 1999 and 2018, using contemporary heterogeneous panel approaches and pooled mean group (PMG), and found that renewable energy consumption alleviates environmental pollution in both the long- and short-run. In a recent study, Özkan, Ahmed, et al. (2024) examined the environmental impact of the energy transition, political globalization, and natural resources on environmental degradation in Turkey, using quantile–quantile multivariate regression approach, and found energy transition lowers carbon emissions in all quantiles. Furthermore, Ahmed et al. (2022) examined the effect of democracy and clean energy on ecological footprints in Pakistan using the novel Augmented ARDL approach, finding that democracy and clean energy mitigate ecological footprints while population density increases them.

The complex relationship between economic growth and environmental sustainability is evident in numerous studies, each highlighting different aspects of this dynamic. Danish et al. (2019) discovered that economic growth and biocapacity lead to a rise in ecological footprints, although no direct causality was found between growth and footprint changes. Yang and Usman (2021) confirmed that economic growth substantially increases ecological footprints in the world's top ten healthcare-spending countries. Similarly Aytun et al. (2024) found that economic growth contributes to the overall ecological footprint in 19 middle-income countries. Supporting the Environmental Kuznets Curve (EKC) hypothesis, Hassan et al. (2019) demonstrated that economic growth initially causes environmental degradation but may lead to improvements over time. This is further validated by Yıldırım et al. (2024) and Sultana et al. (2023) by showing that per capita GDP and renewable energy consumption significantly influence carbon emissions. In contrast, Yilanci and Pata (2022) discovered that the G7 countries do not support the EKC hypothesis since causal relationships show a consistent line and do not support an inverted U-shaped relationship between environmental pollution and economic growth. Additionally, Sharma et al. (2021) emphasized regional variations, revealing that per capita income and population density profoundly impact the ecological footprint in South and Southeast Asian nations. Ozkan et al. (2024), using a quantile-based approach, found that natural resource dependency and economic growth negatively affect environmental quality, while financial globalization positively influences the environment. Similar results have been observed by Ozkan et al. (2024) in China.

The literature generally suggests that while economic growth often exacerbates ecological footprints, its negative environmental impacts can be mitigated by renewable energy consumption and other sustainable practices. For instance, Pata et al. (2023) highlight that GDP has a significantly increasing effect on renewable energy consumption in G7 counties, which indicates that growth in the economy can derive investments in sustainable energy solutions. By the same token, Li et al. (2022) revealed that renewable energy promotes economic growth and improves environmental conditions across 120 countries, though its impact varies with urbanization rates. Moreover, Destek, Oğuz, et al. (2024) examined high-income developing nations (BRICS-T) for the period from 1995 to 2020, using the CS-ARDL technique, and found that the usage of renewable energy improves environmental quality, even if economic growth harms environmental quality. Similar results have been observed by Destek, Yıldırım, et al. (2024) in 11 transition economies. However, studies by Öcal et al. (2020) and Cutcu et al. (2023) discovered the exacerbating effects of non-renewable energy consumption and trade openness on environmental degradation, with both factors markedly increasing ecological footprints in Turkey and the ten fastest-developing countries. Using Wavelet quantile-based techniques in Turkey between 2000 and 2019, Özkan, Coban, et al. (2024); Özkan, Degirmenci, et al. (2024) discovered that political globalization positively affects environmental quality across all quantiles, while economic growth has negative impacts at lower quantiles.

The impact of trade openness on environmental sustainability presents a complex and varied picture across different regions. Lu (2020) found that in 13 Asian countries from 1973 to 2014, trade openness modestly mitigates ecological footprints, though the overwhelming influence of real income and energy consumption requires urgent sustainable policy interventions. Similarly, Destek and Sinha (2020) supported the EKC hypothesis in OECD countries from 1980 to 2014. The findings reveal that increased trade openness correlates with reduced ecological footprints and demonstrating a U-shaped relationship between economic growth and ecological footprints. In contrast, Aydin and Turan (2020) observed inconsistencies in BRICS nations, where the impact of trade openness on ecological footprints varied, which demands the need for region-specific policies. Kongbuamai et al. (2020) reported that in Thailand, from 1974 to 2016, trade openness, along with economic growth and energy consumption, increased ecological footprints, although tourism and population density helped reduce them. In sub-Saharan Africa, Okelele et al. (2022) found that trade openness decreased ecological footprints per capita across 23 countries from 1990 to 2015 while also identifying an inverted-U relationship between ecological footprint and GDP per capita. Abdi and Hashi (2024) explored the impacts of energy consumption, industrialization, and urbanization on environmental sustainability in Somalia from 1990 to 2020, using the bounds-testing approach. Their ARDL model findings indicate that trade openness and economic growth significantly exacerbate environmental pollution in Somalia in both the short- and long-run.

Furthermore, the literature presented a multifaceted relationship between population density and environmental sustainability across various regions. Supporting the EKC hypothesis, Gupta et al. (2022) found that in Bangladesh, population density and urbanization significantly increase ecological footprints. Anser et al. (2020) echoed these findings in their global study of 130 countries, showing that population density and economic growth significantly impact ecological footprints, also in line with the EKC hypothesis. Conversely, Hussain et al. (2022) reported that in Pakistan, higher population density negatively impacts ecological footprints, which suggests that well-distributed populations can reduce environmental degradation. Chen et al. (2022) discovered that globally, human capital initially increases but eventually reduces ecological footprints, with urbanization moderating this effect. Higher urbanization levels require more human capital to improve environmental quality. In the Barcelona Metropolitan Region, Muñiz and García-López (2019) found that polycentrism helps reduce ecological footprints, though the impact of population density remains contentious. Kovács et al. (2020) demonstrated significant spatial disparities in the Budapest Metropolitan Region, where higher disposable income in the core city led to increased footprints, while suburban areas saw rising footprints due to younger, more affluent households and higher heating needs. The existing studies indicate that while population density and urbanization can exacerbate environmental stress, strategic urban planning and human capital development are crucial for mitigating their negative impacts and promoting sustainable development.

Despite extensive research on the effects of globalization, renewable energy consumption, economic growth, trade openness, and urbanization on ecological footprints and carbon emissions, several critical gaps still need to be addressed. Most notably, the SSA region has been under-investigated, with existing studies primarily focusing on CO_2 emissions rather than a broader measure like ecological footprints (Abdi, 2023; Asongu & Odhiambo, 2019; Salahuddin et al., 2020; Warsame et al., 2023). Previous investigations have highlighted the significant impact of economic growth and globalization on increasing ecological footprints, but the mitigating effects of renewable energy and trade openness have shown inconsistent results across different regions. Additionally, the role of population density in environmental sustainability remains contentious, with studies showing both positive and negative impacts depending on the context. Moreover, there is a notable absence of comprehensive analyses that holistically integrate these factors to understand their combined effects on environmental sustainability. Existing research tends to focus on individual factors in isolation or within specific regional contexts, which limits the generalizability of the findings. Our study aims to address these gaps by focusing on the SSA, using ecological footprints and CO_2 emissions as dependent variables to provide a more comprehensive measure of environmental impact.

3. Methodology

3.1. Data and variables

This study utilizes annual panel data from 1994 to 2021 to examine the impact of globalization, renewable energy consumption, economic growth, trade openness, and population density on ecological footprints and environmental degradation in 34 SSA countries. The explained variables are ecological footprints and environmental pollution. The regressors include globalization, renewable energy consumption, economic growth, trade openness, and population density. These variables were chosen for their significant influence on environmental outcomes. Globalization often drives economic activities and resource utilization, which influences environmental quality (Ahmed et al., 2019; Yang & Usman, 2021). Renewable energy consumption mitigates environmental impact by reducing reliance on fossil fuels and lowering GHG emissions (Abdi, 2023; Sharma et al., 2021). Economic growth can variably affect environmental degradation, with higher GDP potentially leading to increased pollution or enabling investments in cleaner technologies (Hassan et al., 2019; Hussain et al., 2022). Trade openness influences the scale and composition of economic activities, thereby impacting environmental outcomes through increased production and consumption (Aydin & Turan, 2020; Kongbuamai et al., 2020; Lu, 2020). Population density affects resource use and waste generation, with higher densities typically leading to greater environmental pressures (Hussain et al., 2022; Kongbuamai et al., 2020). Data were sourced from reputable institutions such as the World Development Indicators (WDI) and the KOF Swiss Economic Institute. Detailed descriptions of data sources, symbols, and measurement units are provided in Table 1.

3.2. Model specification

Building on empirical studies by Dar and Asif (2018), Sinha and Shahbaz (2018), Kongbuamai et al. (2020), and Solarin et al. (2017), this research extends their scope by collectively analyzing the effects of globalization, renewable energy consumption, economic growth, trade openness, and population density on ecological footprints and environmental pollution. All variables are log-transformed to enhance elasticity comparisons, mitigate heteroscedasticity, and reduce data

Table 1
Variables, symbols, measurement unit, and sources.

Variable	Code	Measurement	Source
Ecological footprints	EF	Global hectares (gha)	Global Footprint Network
Carbon emissions	CO_2	Metric tons per capita of CO_2 emissions	WDI
Globalization	GLO	KOF Globalization Index	KOF Swiss Economic Institute
Renewable energy consumption	REC	% of total final energy consumption	WDI
Economic growth	EG	GDP, constant 2015 US$	WDI
Trade openness	TO	Sum of exports and imports (% of GDP)	WDI
Population density	PD	People per square kilometer	WDI

fluctuations, resulting in more robust estimations than basic linear specifications. In Model I, where the ecological footprint is the explained variable, the variables' linear interaction is systematically formulated and articulated through equation (1) as presented:

$$InEF_{it} = \alpha_0 + \alpha_1 InGLO_{it} + \alpha_2 InREC_{it} + \alpha_3 InGDP_{it} + \alpha_4 InTO_{it} + \alpha_5 InPD_{it} + \mu_{it} \quad (1)$$

where EF represents ecological footprints, GLO denotes globalization, REC stands for renewable energy consumption, GDP signifies gross domestic product, TO represents trade openness, and PD denotes population density, with α_1 through α_5 as the coefficients for these variables, and μ as the error term. In Model II, where environmental pollution is the dependent variable, the linear connection among the variables is defined and encapsulated within equation (2), as shown below:

$$InCO_{2it} = \beta_0 + \beta_1 InGLO_{it} + \beta_2 InREC_{it} + \beta_3 InGDP_{it} + \beta_4 InTO_{it} + \beta_5 InPD_{it} + \varepsilon_{it} \quad (2)$$

where CO_2 represents environmental pollution, ε is the error term, and β_1 through β_5. The subscripts i and t denote country and time, respectively, where i = 1,…,N denotes a country index and t = 1,…,T denotes the time period.

3.3. Econometric strategy

3.3.1. Cross-sectional dependence test

Given the economic interconnections and shared characteristics among SSA nations, cross-sectional dependence (CSD) is likely, potentially biasing estimates and inferences. Ignoring CSD can lead to inaccurate and inconsistent estimations (Sarkodie & Owusu, 2020). To identify CSD, we employ the Pesaran (2004) test. The Pesaran CD test, suitable for both small and large panels, is computed as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \quad (3)$$

where N is the number of cross-sections, T is the time dimension, and $\widehat{\rho}_{ij}$ is the sample estimate of the pairwise correlation of the residuals. The study further utilizes the CSD test, specifically the Lagrange Multiplier (LM) statistic by Breusch and Pagan (1980). This test evaluates the alternative hypothesis, which posits the presence of cross-sectional connectedness, against the null hypothesis, which asserts no cross-sectional reliance. The hypotheses are formally stated as follows:

$$H_o : p_{ij} = p_{ji} = cor\left(\mu_{it}, \mu_{jt}\right) = 0 for j \neq i$$

$$H_a : p_{ij} = p_{ji} = cor\left(\mu_{it}, \mu_{jt}\right) \neq 0 for some j \neq i$$

If there is a significant deviation of the CSD statistic from zero, the null hypothesis of no CSD is rejected, and vice versa.

3.3.2. Slope heterogeneity test

Because ignoring slope heterogeneity could be detrimental to regression analysis, the study examines the presence or absence of heterogeneity in the slope coefficients by employing the Pesaran and Yamagata (2008) test. This test can be computed using the following relation:

$$\overline{\Delta} = \left(\frac{N^{-1}\overline{S} - k}{\sqrt{2k}}\right) \quad (4)$$

where $\overline{S}$ is the average of the individual slope coefficients, and k is the number of regressors. This test determines if slope coefficients significantly vary across cross-sections, which indicates the need for heterogeneous panel estimators. For the small samples are handled by using the biased adjusted version of $\overline{\Delta}$ test:

$$\overline{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\overline{S} - E(\overline{Z}_{iT})}{\sqrt{Var(\overline{Z}_{iT})}}\right) \quad (5)$$

where $E(\overline{Z}_{iT}) = K, Var(\overline{Z}_{iT}) = \frac{2k(T-K-1)}{T+1}$. The null hypothesis of this test posits that all slope coefficients are homogeneous, which means they are constant across all cross-sectional units.

3.3.2. Unit root test

Given the likelihood of CSD in the study's panels, we employ second-generation unit root tests to determine stationarity. Specifically, we use the Cross-sectional Im-Pesaran-Shin (CIPS) and the Cross-sectional Augmented Dickey-Fuller (CADF) tests. The CIPS test addresses CSD by incorporating cross-sectional averages of lagged levels and first differences, which ensures a more robust analysis of panel data stationarity. It can be expressed as follows:

$$\Delta y_{it} = \alpha_i + \delta_i y_{i,t-1} + \theta_1 \overline{y}_{t-1} + \sum_{j}^{k} \theta_{ij} \Delta \overline{y}_{i,t-j} + \sum_{j=0}^{k} \Delta y_{i,t-j} + \varepsilon_{it} \quad (6)$$

where Δ denotes the first difference, $\overline{y}_{t-1}$ is the cross-sectional average of y_{t-1}, and ε_{it} is the error term. Because the two tests are related, the CIPS statistic can be computed as:

$$\text{CIPS} = N^{-1} \sum_{I=1}^{N} CADF_I \quad (7)$$

where $CADF_I$ is the t statistics in the CADF.

3.3.3. Tests for cointegration

To investigate long-term relationships, we utilize the Pedroni (1999, 2004) and Kao (1999) panel cointegration tests. Unlike traditional cointegration tests, the Pedroni test accommodates panel-specific fixed effects and time trends, allowing the autoregressive (AR) coefficient to vary across panels. This test provides both within-dimension and between-dimension statistics, which enhances the robustness of our analysis. The Pedroni test is specified as follows:

$$Y_{it} = \alpha_i + \delta_{it} + \beta_i X_{it} + \epsilon_{it} \quad (8)$$

where Y_{it} is the dependent variable, X_{it} are the independent variables, α_i are individual fixed effects, and δ_{it} captures deterministic trends. The null hypothesis of no cointegration is rejected if the test statistics are significant. The Kao (1999) test, further validating cointegration while accounting for heterogeneity and CSD, follows similar principles.

3.3.4. PCSE and FGLS estimators

This study employed two advanced econometric techniques to estimate the long-run results: the PCSE estimator, introduced by Beck and Katz (1995), and the FGLS estimator, initially developed by Parks (1967) and later refined by Doran and Kmenta (1986). The PCSE approach is particularly robust against non-spherical error structures. It is well-suited for large panels, as demonstrated in studies by White (1980), White and Domowitz (1984), and Liang and Zeger (1986), which focus on datasets with numerous cross-sectional units and relatively short time dimensions (N > T). Meanwhile, the FGLS estimator incorporates both cross-sectional correlation and heteroscedasticity in panel data, which assures a thorough treatment of panel-specific parameter variations.

3.3.5. Driscoll-Kraay standard errors

To account for cross-sectional dependence, serial correlation, and heteroscedasticity, the study utilizes Driscoll-Kraay standard errors, which provide consistent estimates even in the presence of these issues. The variance–covariance matrix with Driscoll-Kraay standard errors is specified as follows:

$$Var(\widehat{\beta}) = (X'X)^{-1}\left(\sum_{t=1}^{T}\sum_{s=1}^{T}\omega_{ts}\right)(X'X)^{-1} \tag{9}$$

where ω_{ts} represents the covariance between residuals at times t and s.

3.3.6. Dumitrescu-Hurlin causality test

There are various benefits to contrasting panel data models with time series methods for causality testing. Cross-sectional data can be employed to identify potential causal connections (Heidarian & Green, 1989). In this context, the Dumitrescu and Hurlin (2012) panel causality test is utilized to determine the direction of causality between variables, assuming that certain cross-sections in the panel may be causally related, but not necessarily all. Notably, for heterogeneous panels, the Dumitrescu-Hurlin panel causality test is applicable for both N > T and N < T. Using this approach, the study examines the causative relationships between globalization, renewable energy consumption, economic growth, trade openness, population density, ecological footprints, and environmental pollution. The test statistic is calculated as follows:

$$y_{it} = \alpha_{it} + \sum_{i=1}^{k}\theta_i^{(k)}y_{i,t-k} + \sum_{i=1}^{k}\delta_i^{(k)}x_{i,t-k} + \varepsilon_{it} \tag{10}$$

where $\theta_i^{(k)}$ and $\delta_i^{(k)}$ demonstrates lag and slope parameters that vary across groups, k signifies the lag orders and is considered to be the same for all cross-sections units, and α_{it} denotes individual effects that are intended to be fixed in the time dimension. Moreover, the null hypothesis suggests that there is no homogeneous causation across all cross-sections, while the alternative hypothesis indicates evidence of at least one causal linkage between the variables. The null and alternative hypothesis for evaluating the Dumitrescu–Hurlin panel causality is expressed as follows:

$$\begin{gathered} H_0 : \delta_i = 0 \forall_i = 1, \cdots, N \\ H_1 : \delta_i = 0 \forall_i = 1, \cdots, N \\ H1 : \delta_i \neq 0 \forall_i = N+1, N+2, \cdots, N \end{gathered} \tag{11}$$

4. Empirical results and discussion

1.1. Descriptive statistics and correlation analysis

Table 2 presents the descriptive statistics and correlation analysis for the study's parameters. The findings reveal that economic growth has the highest average values, while carbon emissions have the lowest. Notably, the ecological footprint and globalization display relatively stable trends, with minimal standard deviations of 0.182 and 0.099, respectively. In contrast, population density exhibits significant variability, indicated by the highest standard deviation of 0.586. Most variables, except for ecological footprints, carbon emissions, and economic growth, are negatively skewed. Additionally, all variables exhibit positive excess kurtosis. The Jarque-Bera test results indicate that the assumption of normal distribution for these parameters cannot be confirmed. All observations in the dataset are consistent, with a total of 952 data points for each variable. In the correlation analysis presented in Table 2 Panel B, globalization (0.675), economic growth (0.939), and trade openness (0.464) are positively correlated with carbon emissions. Conversely, renewable energy consumption (−0.729) and population density (−0.187) are negatively correlated with carbon emissions. Furthermore, all explanatory variables, except renewable energy consumption and population density, exhibit a positive correlation with the ecological footprint. This suggests that increases in these explanatory variables generally degrade environmental sustainability, whereas increases in renewable energy consumption and population density improve it.

1.2. Cross-sectional dependence test and heterogeneity test

The initial and crucial step in panel data analysis is to determine the presence of CSD among the series. If the series exhibits CSD, traditional unit root tests, which assume cross-sectional independence, yield false and unreliable results. Consequently, this investigation employed several tests to detect CSD: the Breusch and Pagan (1980) LM test, the bias-corrected LM test, the Pesaran (2004) scaled LM test, and the

Table 3
Cross-sectional dependence test outcomes.

H_0: No cross-section dependence				
Variable	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
lnEF	3485.165	87.298	86.669	11.398
	[0.000]	[0.000]	[0.000]	[0.000]
$lnCO_2$	5982.909	161.866	161.236	23.171
	[0.000]	[0.000]	[0.000]	[0.000]
lnGLO	12175.64	346.744	346.115	109.534
	[0.000]	[0.000]	[0.000]	[0.000]
lnREC	6376.420	173.614	172.984	37.681
	[0.000]	[0.000]	[0.000]	[0.000]
lnGDP	7689.635	212.819	212.189	46.332
	[0.000]	[0.000]	[0.000]	[0.000]
lnTO	3116.097	76.280	75.650	9.760
	[0.000]	[0.000]	[0.000]	[0.000]
lnPD	15390.250	442.714	442.084	124.045
	[0.000]	[0.000]	[0.000]	[0.000]

Note: The values in the parenthesis […] indicate the p-values.

Table 2
Descriptive summary and correlation analysis.

Panel A: Characteristics of the data							
	lnEF	$lnCO_2$	lnGLO	lnREC	lnGDP	lnTO	lnPD
Mean	0.131	−0.531	1.642	1.810	3.040	1.749	1.594
Maximum	0.605	0.927	1.857	1.993	4.040	2.245	2.802
Minimum	−0.248	−1.662	1.360	0.881	2.280	0.616	0.277
Std. Dev.	0.182	0.582	0.099	0.224	0.388	0.207	0.586
Skewness	0.583	0.421	−0.539	−2.230	0.649	−0.691	−0.202
Kurtosis	2.686	2.585	3.094	7.936	2.622	5.079	2.642
Jarque-Bera	57.758	34.962	46.368	1755.474	72.433	247.224	11.570
Probability	0.000	0.000	0.000	0.000	0.000	0.000	0.003
Panel B: Correlation analysis							
lnEF	1.000						
$lnCO_2$	0.679	1.000					
lnGLO	0.310	0.675	1.000				
lnREC	−0.687	−0.729	−0.572	1.000			
lnGDP	0.712	0.939	0.668	−0.691	1.000		
lnTO	0.394	0.464	0.423	−0.333	0.490	1.000	
lnPD	−0.411	−0.187	0.155	0.038	−0.190	−0.215	1.000

Pesaran (2015) CD test. Table 3 presents the outcomes of these cross-sectional dependence analyses. The results indicate that the null hypothesis of no cross-sectional dependence is rejected at the 1 % significance level for all series, which provides strong evidence of cross-sectional dependence among the countries under study. On the other hand, the study utilized the Pesaran and Yamagata (2008) test to assess whether the slope coefficients are homogeneous or heterogeneous in their distribution. Recognizing slope heterogeneity is essential, as its neglect can affect regression results and lead to erroneous hypothesis testing. The findings, presented in Table 4, align with the conclusions of Chen et al. (2022) and Ahakwa (2023), which demonstrates that the null hypothesis of slope homogeneity for both models is rejected. Consequently, the rest of the research employs econometric techniques robust to slope heterogeneity and cross-sectional dependence.

1.3. Panel unit root analysis

Given that traditional unit root tests are inadequate for addressing CSD among parameters, this study employed the CIPS and CADF panel unit root tests, as outlined by Pesaran (2014), which account for CSD. Table 5 presents the results of these tests. The findings indicate that all variables, except lnEF, $lnCO_2$, lnGLO, and lnTO, are non-stationary at level I(0). However, at their first difference (I(1)), all variables become stationary. This suggests that the series has the potential to become co-integrated over time.

1.4. Panel cointegration tests

The study employed the Pedroni and Kao cointegration tests to evaluate the long-run relationships among the variables. As illustrated in Table 6, the results of the Pedroni test indicate a cointegration relationship in Models I and II, as the null hypothesis of no cointegration is rejected under all methods. This is evidenced by the probability values of the modified PP, PP, and ADF statistics being less than the 1 % significance level. Additionally, the Kao cointegration test, which accounts for heterogeneity and cross-sectional dependence, corroborates the Pedroni test results, confirming the cointegration relationship among the series. The overall results suggest rejecting the null hypothesis of no cointegration between the ecological footprint, environmental pollution, and the independent variables, in favor of the alternative hypothesis that they are cointegrated. The confirmation of long-run cointegrating relationships meets the requirement for estimating the long-run elasticities of both models. Therefore, the main estimations follow the cointegration analysis.

1.5. Model estimations – PCSE, FGLS, and Driscoll-Kraay standard errors results

Tables 7 and 8 present the effects of the long-run elasticity of the independent variables on the dependent variables for the ecological footprint and carbon emission models. We employ three distinct tests—PCSE, FGLS, and Driscoll-Kraay standard errors—to ensure robust results, with the latter two enhancing the robustness of the PCSE results. The results indicate that globalization significantly lowers the ecological footprint in SSA countries. Specifically, a 1 % increase in globalization is associated with a 0.519 % improvement in environmental quality at the 1 % level of significance. The findings indicate that globalization significantly contributes to environmental sustainability in SSA countries. Conversely, globalization has been shown to have a significant positive impact on carbon emissions. A 1 % increase in globalization will increase carbon emissions by 0.496 % at the 1 % significance level. These results align with studies by (Ahmed et al., 2019) and (Shahbaz et al., 2018), who report that globalization increases CO_2 emissions. The duality of these findings features the sophistication of globalization's impact on the region, with positive effects on sustainable practices contrasting with the environmental costs of economic expansion. This balance suggests that the dynamics of globalization in SSA are shaped by factors such as the nature of imported technologies, the structure of trade, and the energy mix driving industrial growth.

Similarly, renewable energy consumption demonstrates a significant negative impact in both models across all estimators. Specifically, in the ecological footprint and carbon emissions models, a unit increase in renewable energy consumption reduces the ecological footprint by 0.386 % and carbon emissions by 0.373 %, respectively, at the 1 % threshold level. This proposes the transformative potential of renewable energy adoption in SSA, where energy systems have traditionally been dominated by fossil fuels such as coal, oil, and natural gas. The transition to renewable energy in SSA could drive substantial environmental benefits, including reductions in greenhouse gas emissions and improvements in air quality. Additionally, by diversifying energy sources, renewable energy adoption can contribute to building more resilient and sustainable energy systems in the region. These findings are consistent with those of Sahoo and Sethi (2021) for developing countries, Usman and Makhdum (2021) for the BRICS-T region, Abdi (2023) in the SSA countries, and Ansari et al. (2021) for leading renewable energy countries. For SSA, where many countries face energy poverty and infrastructure limitations, investing in renewable energy not only supports environmental sustainability but also promotes energy access and economic growth.

Furthermore, all estimators in both models consistently show that economic growth significantly negatively impacts environmental quality in SSA countries. Specifically, a 1 % increase in economic growth leads to a 0.233 % rise in the ecological footprint and a 1.171 % increase

Table 4
Heterogeneity test results.

	Model I: lnEF		Model II: $lnCO_2$	
H_0: coefficient slopes are homogeneous				
	Statistic	P-value	Statistic	P-value
$\tilde{\Delta}$	19.177	0.000	29.005	0.000
$\tilde{\Delta}$ Adjusted	22.143	0.000	33.493	0.000

Table 5
Second-generation unit root tests.

Variables	Level		1st Difference	
	CIPS	CADF	CIPS	CADF
lnEF	−2.390***	−1.951	−5.796***	−4.183***
$lnCO_2$	−2.442***	−2.357***	−4.846***	−3.878***
lnGLO	−2.907***	−2.699***	−4.814***	−3.972***
lnREC	−1.922	−1.801	−4.695***	−3.431***
lnGDP	−1.710	−1.726	−4.159***	−2.996***
lnTO	−2.185**	−2.166***	−5.058***	−3.665***
lnPD	−2.023	−3.128***	−2.374***	−2.725***

Note: ***, **, * denote significance levels at 1%, 5% and 10%, respectively.

Table 6
Pedroni and Kao cointegration test results.

	Model I: lnEF		Model II: $lnCO_2$	
	Statistic	p-value	Statistic	p-value
Pedroni test for cointegration				
Modified Phillips-Perron t	3.178	0.001	4.530	0.000
Phillips-Perron t	−8.842	0.000	−3.031	0.001
Augmented Dickey-Fuller t	−9.695	0.000	−4.542	0.000
Kao test for cointegration				
Modified Dickey-Fuller t	−2.615	0.005	−1.335	0.091
Dickey-Fuller t	−3.416	0.000	−2.946	0.002
Augmented Dickey-Fuller t	−1.099	0.136	−0.019	0.493
Unadjusted modified Dickey-Fuller t	−9.214	0.000	−2.848	0.002
Unadjusted Dickey-Fuller t	−6.454	0.000	−3.788	0.000

Table 7
Results from the PCSE, FGLS, and Driscoll-Kraay estimators (Model I: lnEF).

	PCSE			FGLS			Driscoll-Kraay S.E		
	Coeff.	std. err.	z-stat.	Coeff.	std. err.	z-stat.	Coeff.	std. err.	t-stat.
lnGLO	−0.519***	0.037	−13.880	−0.497***	0.027	−18.430	−0.519***	0.076	−6.800
lnREC	−0.386***	0.013	−30.570	−0.421***	0.011	−37.400	−0.386***	0.016	23.720
lnGDP	0.233***	0.010	22.360	0.216***	0.009	23.720	0.233***	0.023	10.270
lnTO	0.052***	0.015	3.550	0.069***	0.011	6.370	0.052*	0.028	1.850
lnPD	−0.075***	0.004	−19.400	−0.088***	0.004	−21.770	−0.075***	0.006	12.280
Constant	1.002***	0.073	13.770	1.069***	0.051	20.810	1.002***	0.077	13.020
Obs.	952			952			952		
R^2	0.717						0.717		
Countries	34			34			34		

Note: ***, **, * denote significance levels at 1%, 5% and 10%, respectively. Coeff. and std err. are the coefficients and standard errors, respectively.

Table 8
Results from the PCSE, FGLS, and Driscoll-Kraay estimators (Model II: lnCO_2).

	PCSE			FGLS			Driscoll-Kraay S.E		
	Coeff.	std. err.	z-stat.	Coeff.	std. err.	z-stat.	Coeff.	std. err.	t-stat.
lnGLO	0.496***	0.097	5.110	0.358***	0.061	5.840	0.496***	0.178	2.790
lnREC	−0.373***	0.019	−19.170	−0.444***	0.027	−16.430	−0.373***	0.023	16.060
lnGDP	1.171***	0.022	53.080	1.152***	0.018	65.080	1.171***	0.053	22.030
lnTO	−0.036**	0.016	−2.260	−0.034	0.024	−1.430	−0.036	0.025	−1.430
lnPD	−0.049***	0.007	−6.650	−0.029***	0.009	−3.390	−0.049***	0.016	−3.000
Cons	−4.090***	0.162	−25.180	−3.710***	0.112	−33.070	−4.090***	0.182	22.470
Obs.	952			952			952		
R^2	0.898						0.898		
Countries	34			34			34		

in CO_2 emissions, both at the 1 % significance level. This reflects the environmental costs associated with economic expansion, as many SSA countries rely heavily on natural resource exploitation and energy-intensive activities to drive growth. These practices, while promoting economic development, often result in higher pollution levels, increased energy consumption, and exacerbated climate change, thereby degrading overall environmental quality. This stresses the relentless tension between economic growth and environmental sustainability, particularly in regions like SSA, where development priorities often overshadow ecological considerations. The substantial environmental impact of economic expansion emphasises the critical necessity for adopting sustainable growth strategies that mitigate environmental harm while fostering economic progress. Our study's findings are consistent with numerous empirical studies from various countries, including Danish et al. (2019) for BRICS economies, Aşici and Acar (2015) for developing countries, Ansari et al. (2021) for top renewable energy countries, and Destek (2020) for Central and Eastern European countries. This displays the global nature of the growth-environment trade-off. In the context of SSA, this accentuates the essence of combining environmentally conscious practices into development frameworks to ensure long-term sustainability.

Additionally, trade openness is found to have a significant dual impact on environmental indicators in SSA. A 1 % increase in trade openness leads to a 0.052 % rise in the ecological footprint at the 1 % significance level. This reflects the environmental pressures of the region's resource-intensive exports and the ecological costs of imported goods. These trade activities contribute significantly to the ecological footprint, both within SSA and in its trading partners, as the environmental burdens of production and consumption are shared across borders. For SSA, where exports are predominantly raw materials and natural resources, the environmental strain is amplified, further exacerbating resource depletion and ecological degradation. This finding is consistent with the results of (Kongbuamai et al., 2020b) for Thailand and (Imamoglu, 2018) for Turkey. Conversely, trade openness has a negative and significant effect on carbon emissions, with a 1 % increase in trade openness resulting in a 0.036 % reduction in CO_2 emissions. This reduction could be attributed to the diffusion of cleaner technologies and practices through international trade, as well as a shift in production processes towards lower-emission methods. In SSA, this may reflect the growing adoption of energy-efficient practices and technologies in industries catering to global markets, driven by international environmental standards and regulations. These results are consistent with the findings of (Dogan & Seker, 2016b; Jebli et al., 2013), which indicate that trade can facilitate environmental improvements in terms of carbon emissions, even as it imposes broader ecological pressures. For SSA, balancing these opposing effects is crucial to leveraging trade as a driver of sustainable development.

Furthermore, the coefficient of population density demonstrates a negative and significant effect on both ecological footprint and carbon emissions in SSA. Specifically, a 1 % increase in population density is associated with a 0.075 % and a 0.049 % reduction in the ecological footprint and CO_2 emissions, respectively. This outcome may stem from the concentration of populations in urban areas, which fosters the development of efficient infrastructure, compact living spaces, and shared public services. The observed decrease in the ecological footprint and environmental pollution with rising population density suggests that well-managed urbanization can serve as a catalyst for environmental improvement in SSA. This finding aligns with the results of Aşici and Acar (2015) and Dogan et al. (2020), which reinforces the potential environmental benefits of urban concentration. However, it contrasts with the conclusions of Sahoo and Sethi (2021) and Ohlan (2015), who reported a positive association between population density and CO_2 emissions. In the context of SSA, where urbanization is rapidly expanding, these results underline the significance of strategic urban planning and investment in sustainable infrastructure to exploit the environmental advantages of higher population densities. The robustness of these findings is further supported by the R-square values of the models, which stand at 0.717 for the ecological footprint model and 0.898 for the CO_2 emissions model. This indicates a strong explanatory power of the independent variables in capturing the variations in environmental outcomes.

1.6. Panel causality test

The coefficients obtained from the long-run elasticities provide significant insights. However, these results do not clarify the causal relationships among the analyzed variables. Policymakers require information on the directions of causality to implement appropriate regulations effectively. Therefore, this study employed the Dumitrescu and Hurlin (2012) causality test to determine the causal relationships between the parameters. Table 9 presents the results of the causality analysis. The study observed a bidirectional relationship between the explanatory variables and the ecological footprint, except for trade openness. The two-way relationships between ecological footprint and variables such as globalization, renewable energy consumption, economic growth, and population density suggest that changes in one aspect will significantly influence the others. This interconnectedness highlights the complexity of managing ecological impacts, which requires a comprehensive understanding of how these factors interact and affect each other. Furthermore, the results reveal the presence of two-way causal effects between renewable energy consumption and carbon emissions. This strengthens the long-run results of the study, which suggest that improved energy access through renewables not only limits carbon emissions but also promotes economic development. These results are consistent with the findings of Le and Sarkodie (2020) and Dogan and Seker (2016a).

Table 9
Dumitrescu–Hurlin causality test results.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Direction of causality
Model I: Ecological footprints			
lnGLO does not homogeneously cause lnEF	4.548***	5.548	Bidirectional
lnEF does not homogeneously cause lnGLO	3.243**	2.451	
lnREC does not homogeneously cause lnEF	3.774***	3.711	Bidirectional
lnEF does not homogeneously cause lnREC	3.367***	2.744	
lnGDP does not homogeneously cause lnEF	3.847***	3.885	Bidirectional
lnEF does not homogeneously cause lnGDP	3.402***	2.827	
lnTO does not homogeneously cause lnEF	3.123**	2.166	Unidirectional
lnEF does not homogeneously cause lnTO	2.888	1.608	
lnPD does not homogeneously cause lnEF	7.376***	12.260	Bidirectional
lnEF does not homogeneously cause lnPD	3.163**	2.262	
Model II: CO_2 emissions			
lnGLO does not homogeneously cause lnCO_2	5.495***	7.795	Bidirectional
lnCO_2 does not homogeneously cause lnGLO	4.251***	4.843	
lnREC does not homogeneously cause lnCO_2	4.555***	5.565	Bidirectional
lnCO_2 does not homogeneously cause lnREC	3.237***	2.435	
lnGDP does not homogeneously cause lnCO_2	6.335***	9.788	Unidirectional
lnCO_2 does not homogeneously cause lnGDP	2.834	1.481	
lnTO does not homogeneously cause lnCO_2	2.938	1.727	Unidirectional
lnCO_2 does not homogeneously cause lnTO	4.782***	6.102	
lnPD does not homogeneously cause lnCO_2	6.681***	10.610	Bidirectional
lnCO_2 does not homogeneously cause lnPD	7.389***	12.291	

Note: *** and ** denote significance levels at 1% and 5%, respectively.

Similarly, the findings confirmed the causality between globalization and carbon emissions. This implies that globalization and carbon emissions have a mutually reinforcing connection, with increased globalization leading to higher carbon emissions due to the transportation of goods across long distances, as SSA countries are primarily importers. These results align with Pata (2021), who found bidirectional causation between globalization and carbon emissions in Russia. Additionally, unidirectional causation from economic growth to carbon emissions was revealed, which indicates that rapid economic growth is heavily dependent on extensive energy use. This serves as a warning that GHG emissions are increasing, as economic growth drives demand for manufacturing and energy-intensive operations needed to meet people's varied requirements (Abdi, 2023). Moreover, a one-way link from carbon emissions to trade openness was identified. This implies that increased carbon emissions may hinder trade openness, which suggests that worsening environmental conditions could negatively impact the region's ability to engage in and benefit from international trade. Furthermore, a two-way causal relationship between population density and carbon emissions was observed. This suggests that population density can influence whether carbon emissions increase or decrease.

5. Conclusion and evidence-based policy strategies

Tackling the dual challenges of economic growth and environmental sustainability is vital for addressing the pressing climate change issues in SSA. Promoting clean energy sources and understanding the effects of globalization are key strategies proposed to enhance environmental quality while supporting sustainable economic development. Many SSA countries have increasingly embraced globalization, which often results in significant environmental repercussions. Thus, this study aims to investigate the impact of globalization, renewable energy consumption, economic growth, trade openness, and population density on the ecological footprint and environmental degradation in SSA nations from 1994 to 2021. The study utilized a suite of econometric techniques, including PCSE, FGLS, and Driscoll-Kraay estimators. The analysis identified the presence of cross-sectional dependence and rejected the null hypothesis of slope coefficient homogeneity. As a result, second-generation unit root tests, such as CADF and CIPS, were employed to confirm that the variables exhibit a mixed order of stationarity, i.e., I(0) and I(1). Furthermore, Pedroni and Kao cointegration tests confirmed long-run cointegration relationships among ecological footprint, environmental pollution, and the regressors. Additionally, the Dumitrescu–Hurlin test was applied to determine the direction of causal relationships between the variables.

The analysis reveals that globalization has a mixed impact on environmental outcomes in SSA countries. While it significantly increases the ecological footprint, thereby reducing environmental quality, it simultaneously lowers CO_2 emissions, which reflect the complex trade-offs between economic integration and environmental sustainability. On the other hand, renewable energy consumption plays a transformative role, significantly reducing both the ecological footprint and CO_2 emissions. This indicates the potential of renewable energy adoption to enhance environmental quality by reducing reliance on fossil fuels and mitigating environmental degradation. Moreover, economic growth exhibits a significant positive effect on both the ecological footprint and CO_2 emissions. This indicates that growth mechanisms in SSA are resource-intensive and contribute to higher pollution and energy consumption. Conversely, trade openness shows contrasting effects: while it significantly increases the ecological footprint, it reduces environmental pollution. This suggests that trade activities in SSA, dominated by resource-based exports and imports, contribute to ecological strain but may facilitate access to cleaner technologies that lower emissions. In addition, population density has a noteworthy impact, significantly reducing ecological deterioration, likely due to urbanization-driven improvements in infrastructure and resource efficiency. On the other hand, the Dumitrescu-Hurlin causality test reveals bidirectional relationships between globalization, renewable energy consumption, economic growth, and population density with the ecological footprint in SSA. However, trade openness exhibits a unidirectional causal linkage running from trade openness to the ecological footprint in SSA. Additionally, the analysis identifies that renewable energy consumption, globalization, and population density have a bidirectional causality with CO_2 emissions. Besides, a unidirectional causality runs from economic growth and trade openness towards CO_2 emissions in SSA.

To mitigate the environmental impacts highlighted by the study, SSA countries should adopt the following strategies: Firstly, prioritize investments in renewable energy infrastructure to reduce reliance on fossil fuels and lower the ecological footprint. This will help harness abundant renewable resources, which ensures a sustainable and clean energy supply. Secondly, implement stricter environmental regulations for industries involved in global trade to curb the negative effects of globalization on environmental quality. By enforcing these regulations, countries can ensure that economic activities do not compromise environmental sustainability. Thirdly, promote sustainable economic growth through the adoption of green technologies and practices to minimize pollution and energy consumption. Encouraging businesses to adopt environmentally friendly technologies will lead to a significant reduction in industrial emissions. Fourthly, support urbanization and infrastructure development that enhance environmental quality, such as energy-efficient buildings and public transportation, to further reduce the ecological footprint. This can lead to improved living conditions while simultaneously protecting the environment. Lastly, strengthen environmental monitoring systems and governance frameworks to ensure effective enforcement of regulations and promote transparency in managing environmental impacts. Robust monitoring and governance will enable timely intervention and compliance, ensuring long-term environmental health.

While this study provides significant insights into the impact of globalization, renewable energy consumption, economic growth, trade openness, and population density on ecological footprints and environmental pollution in SSA, it has certain limitations. Firstly, the analysis relies on panel data from 34 SSA countries, which may not fully capture country-specific heterogeneities due to data constraints. Secondly, this study focuses on a limited set of explanatory variables; other potential factors, such as institutional quality, technological advancements, and climate adaptation measures, were not considered but could further enrich the analysis. Future research can address these limitations by exploring additional environmental indicators, such as water pollution or land use changes. Additionally, country-specific or regional case studies using disaggregated data could shed light on localized dynamics and variations within SSA. Incorporating non-linear models or exploring threshold effects (e.g., Kuznets curve) could also reveal whether the relationships identified in this study evolve over different levels of economic development.

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Ethical approval

This study follows all ethical practices during writing. We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

CRediT authorship contribution statement

Abdikafi Hassan Abdi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Siyad Abdirahman Siyad:** Writing – original draft, Investigation. **Mohamed Okash Sugow:** Writing – review & editing. **Omar Mohamed Omar:** Writing – review & editing.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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